

EXPERIMENTAL IDENTIFICATION AND SIMULATION OF TIME AND/OR RATE DEPENDENT REVERSIBLE AND IRREVERSIBLE DEFORMATION REGIONS FOR BOTH A TITANIUM AND NICKEL ALLOY

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ABSTRACT In this paper time and/or rate dependent deformation regions are experimentally mapped out as a function of temperature. It is clearly demonstrated that the concept of a threshold stress (a stress that delineate reversible and irreversible behavior) is valid and necessary at elevated temperatures and corresponds to the classical yield stress at lower temperatures. Also the “infinitely slow” modulus, (E_s) i.e. the elastic modulus of the material if it was loaded at an infinitely slow strain rate, and the “dynamic modulus”, modulus, E_d , which represents the modulus of the material if it is loaded at an “infinitely fast” rate are used to delineate rate dependent from rate independent regions. As demonstrated at elevated temperatures there is a significant difference between the two modulus values, thus indicating both *significant time-dependence* and rate dependence. In the case of the nickel-based super alloy, ME3, this behavior is also shown to be grain size specific. Consequently, at higher temperatures viscoelastic behavior exist below κ (i.e., the threshold stress) and at stresses above κ the behavior is viscoplastic. Finally a multi-mechanism, stress partitioned viscoelastic model, capable of being consistently coupled to a viscoplastic model is characterized over the full temperature range investigated for Ti-6-4 and ME3.

INTRODUCTION: A prerequisite for meaningful assessment of component durability and life, and consequently design of structural components, is the ability to accurately predict stresses, strains, failure modes and their subsequent interaction and evolution occurring within a loaded structure. Furthermore, since constitutive material models provide the required link between stress and strain, this by necessity demands an appropriate constitutive behavior model for any material (be it monolithic or composite) before that material can be certified for use by a designer. In general, metallic constitutive models have assumed the reversible or “elastic” regime to be time-independent and the irreversible or “inelastic” strains were considered to be either time-independent (“plastic”), or more commonly time-dependent (“viscoplastic”). Recent research efforts have determined that strains in the reversible regime can be both time-independent and time-dependent (Saleeb and Arnold, 2001; Arnold et al., 2001) depending on the temperature. Therefore concepts from viscoelasticity, which previously had not been applied to metals, actually need to be applied to the constitutive equations employed to analyze metals. Furthermore, in the regime of time-dependent strains, due to the wide spectrum of rate-dependence of the material in both the reversible and irreversible domains, multiple mechanisms or relaxation spectrums need to be included. The more mechanisms that are used, the more likely the characterized model is to

appropriately model the behavior across all strain rates. The GVIPS (Generalized Viscoplasticity with Potential Structure) model is a comprehensive viscoelastoplastic constitutive model that aims to describe a material's behavior whether in the viscoelastic or viscoplastic region (Saleeb et al. 2001 and Saleeb and Arnold, 2004). Herein, only the characterized viscoelastic portion of the model along with the explicitly experimentally determined threshold stress for a titanium alloy, Ti-6-4, and nickel based alloy, ME3, both fine and coarse grain, will be discussed. The characterization of the multimechanism viscoelastic model is achieved using our fully-automated, material parameter estimator, COMPARE, for details see Saleeb et al. 2004.

PROCEDURES, RESULTS AND DISCUSSION:

The need for an advanced viscoelastoplastic model to analyze the deformation response of both titanium (e.g., Ti-6-4) and nickel based superalloys (e.g., ME3) at elevated temperatures is demonstrated in Figure 1 and 2, where the variation of the moduli and threshold stress (κ) (delineates the reversible and irreversible strain regimes) are plotted as a function of temperature. The modulus E_s represents the “infinitely slow”

modulus, i.e. the elastic modulus of the material if it was loaded at an infinitely slow

strain rate, whereas the modulus E_d represents the "dynamic modulus", $E_d = E_s + \sum_{i=1}^M E_{m,i}$

which is the modulus of the material, if it is loaded at an “infinitely fast” (i.e., very high, 1×10^{-3}) rate. As can be seen in Figure 1, at elevated temperatures there is a significant difference between the two modulus values, indicating that even in the so-called “elastic” range, there is significant time-dependence. Below a temperature of about 300 °C for Ti-6-4 and 593 °C (1100 °F) for ME3, the two moduli are approximately equal, indicating the response of the materials are rate-independent yet not necessarily time-independent in the case of Ti-6-4. Above this temperature, the response is rate-dependent and time-dependent. To appreciate the practical significance of this fact, the operating temperatures typically encountered in aircraft engines (where Ti-6-4 is used) are also noted below the horizontal axis in Figure 1, as well as the occasional, higher-temperature regime encountered during over-temp maneuvers. Clearly, even when one is within the typical engine design range and expecting the material response to be reversible, or "elastic", the materials behavior would in fact be rate-dependent and would deform an additional σ^*/E_s amount of strain over time, where σ^* is the current applied stress. Consequently, at stresses below κ , if classical elasticity methods were used in the design, then this rate dependence, i.e., viscoelastic response, would not be captured.

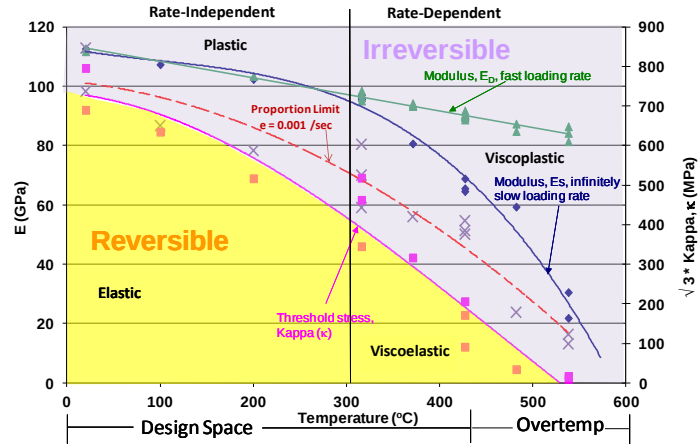


Figure 1: Variation of modulus and threshold stress as a function of temperature for Ti-6-4.

Furthermore, at stresses above κ , the material response is viscoplastic due to the rate- and time-dependence, and similarly using the classical methods of plasticity in analysis and design, would also not be accurate. Figures 1 and 2 further indicate that the experimentally obtained values of

the threshold stress (κ), determined using the viscoelastic subtraction method (Arnold et al. 2001), decreases significantly as a function of increasing temperature and varying grain size (in the case of the ME3 material) and that this threshold stress (κ) is significantly below the traditional “proportional limit” of the material. This factor then leads to the conclusion that irreversible material behavior takes place at stress levels well below those considered using traditional methods for the analysis of metals. If classical design methods were used, the material response below the “proportional limit” would be assumed to be fully reversible, and only the response after the proportional limit would be assumed to be irreversible. However, as is shown in the figures, that assumption could lead to significant inaccuracies in the predictions of the material response.

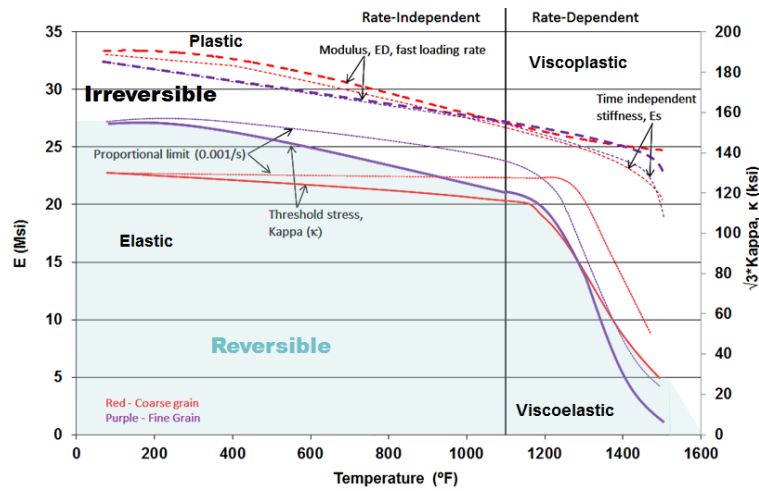


Figure 2: Variation of modulus and threshold stress as a function of temperature for fine and coarse grain ME3.

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